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CHARACTERIZATION OF HYBRID FERROELECTRIC/HTS THIN FILMS FOR TUNABLE MICROWAVE COMPONENTS

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ABSTRACT

Since the discovery of High-Temperature-Superconductors (HTS) in 1986, a diversity of HTS-based microwave components has been demonstrated. Because of their low conductor losses, HTS-based components are very attractive for integration into microwave circuits for space communication systems. Recent advancements have made deposition of ferroelectric thin films onto HTS thin films possible. Due to the sensitivity of the ferroelectric's dielectric constant (ϵ_r) to an externally applied electric field (**E**), ferroelectric/superconducting structures could be used in the fabrication of low loss, tunable microwave components. In this paper, we report on our study of $Ba_{0.5}Sr_{0.5}TiO_3/YBa_2Cu_3O_{7-\delta}$ and $Ba_{0.08}Sr_{0.92}TiO_3/YBa_2Cu_3O_{7-\delta}$ ferroelectric/superconducting thin films on lanthanum aluminate ($LaAlO_3$) substrates. For the (Ba:Sr, 0.50:0.50) epitaxial sample, a ϵ_r of 425 and a loss tangent (tanδ) of 0.040 were measured at 298 K, 1.0 MHz, and zero applied **E**. For the same sample, a ϵ_r of 360 and tanδ of 0.036 were obtained at 77 K, 1.0 MHz, and zero applied **E**. Variations in ϵ_r from 180 to 360 were observed over an applied **E** range of $0\text{V/cm} \leq \mathbf{E} \leq 5.62\times10^4\text{V/cm}$ with little change in tanδ. However, the range of ϵ_r variation for the polycrystalline (Ba:Sr, 0.08:0.92) sample over $0\text{V/cm} \leq \mathbf{E} \leq 4.00\times10^4\text{V/cm}$ was only 3.6 percent while tanδ increased markedly. These results indicate that a lack of epitaxy between the ferroelectric and superconducting layers decreases tuning and increases microwave losses.

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INTRODUCTION

Since the discovery of High-Temperature-Superconductors (HTS) in 1986, it has been possible to fabricate HTS-based planar microwave components such as resonators and filters[1]. The use of HTS films in place of normal conductors (e.g. gold and copper) has greatly reduced conductor losses and consequently insertion losses[2]. Therefore, significant attention has been given to the quality and processing of HTS films as efforts continue towards the inclusion of HTS-based circuits in working systems. One of the areas that has received considerable attention for the insertion of HTS-based components is that of tunable microwave circuits[3]. This requires the development of hybrid superconductor/ferroelectric structures. Ferroelectric materials have a dielectric constant (ϵ_r) that can be altered by an externally applied electric field (**E**). Therefore, optimization of these structures' material properties and careful characterization of their electrical properties should result in high quality, low loss tunable microwave components, such as capacitors, filters, and phase shifters. In this paper, we report on our study of $Ba_{0.5}Sr_{0.5}TiO_3/YBa_2Cu_3O_{7-\delta}$ and $Ba_{0.08}Sr_{0.92}TiO_3/YBa_2Cu_3O_{7-\delta}$ ferroelectric/superconducting thin films on lanthanum aluminate ($LaAlO_3$) substrates.

EXPERIMENTAL

The $Ba_{0.5}Sr_{0.5}TiO_3/YBa_2Cu_3O_{7-\delta}/LaAlO_3$ (BST/YBCO/$LaAlO_3$) structure which was investigated consisted of an 800 nm thick $Ba_{0.5}Sr_{0.5}TiO_3$ film, known hereinafter as BST, deposited on a 300 nm thick $YBa_2Cu_3O_{7-\delta}$ film which coated a 5.0 mm×4.0 mm×0.50 mm $LaAlO_3$ substrate. Both layers were deposited "in-situ" using laser ablation. To elucidate the effects of film microstructure on tuning and loss, metalorganic deposited $Ba_{0.08}Sr_{0.92}TiO_3$ films, known hereinafter as MOD BST films, were prepared at room temperature and post annealed at 700°C to produce polycrystalline films[4]. After deposition of the multilayer structures,

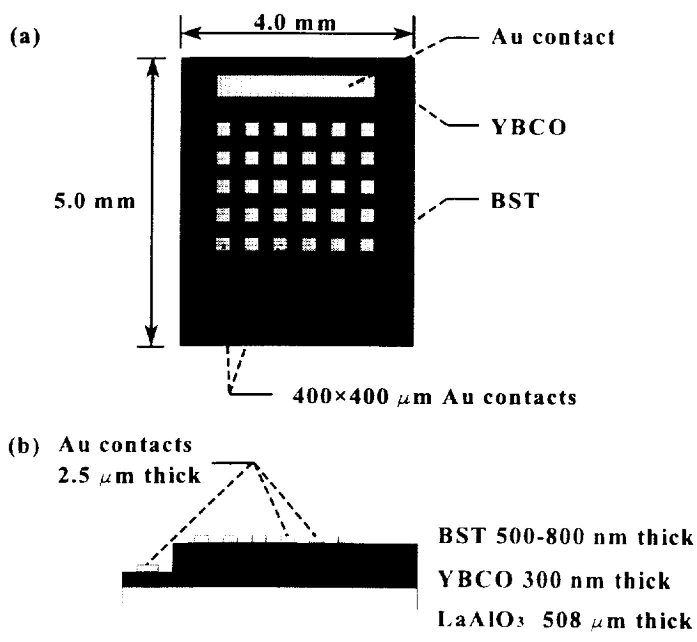

Figure 1. A schematic representation of the $Ba_xSr_{1-x}TiO_3$ (x=0.50,0.08)/$YBa_2Cu_3O_{7-\delta}$/$LaAlO_3$ structure. (a) Top view, (b) Side view.

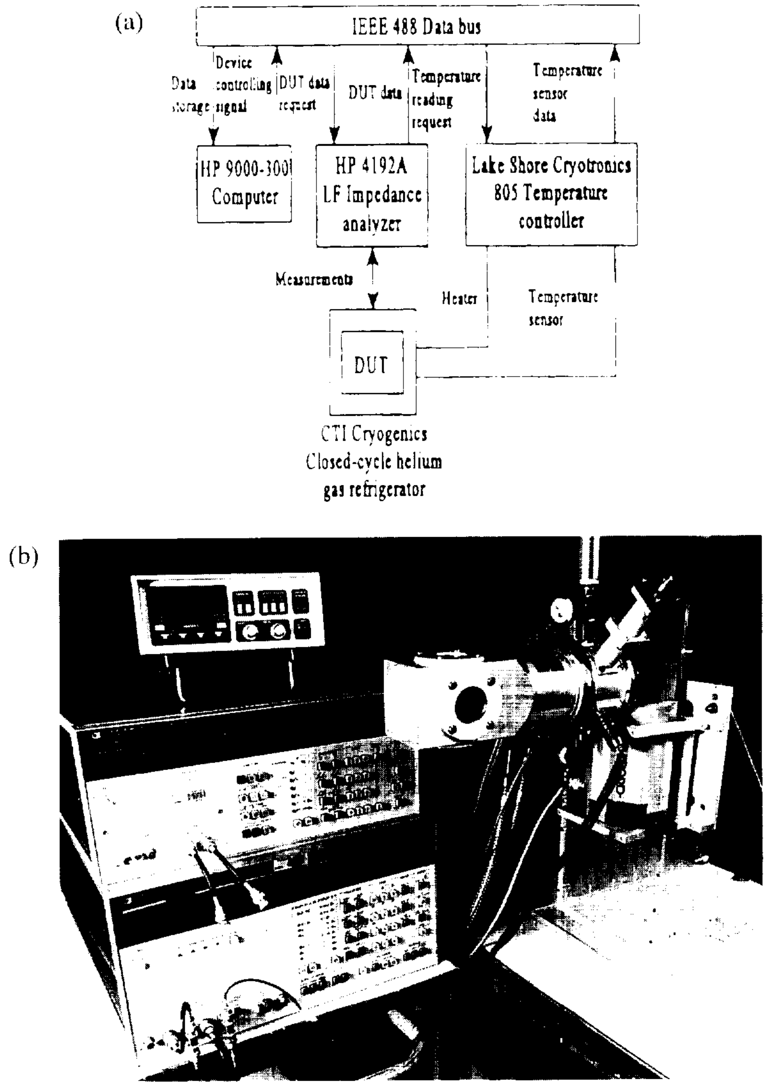

Figure 2. Experimental configuration. (a) Schematic representation, (b) Actual setup.

transition temperatures (T_c) above 89 K were measured for the YBCO films using a four point probe technique indicating that no degradation of the these films occurred as a result of the ferroelectric film deposition. Thirty $400\mu m \times 400\mu m \times 2.5\mu m$ gold (Au) contacts were fabricated on the ferroelectric layer of the structures using standard photolithography and wet etching techniques. In addition, a Au electrode was deposited onto a portion of the structures' YBCO layer, exposed by etching the ferroelectric layer away with a 7.0 percent solution of hydrofluoric (HF) acid. Figure 1 shows a schematic representation of the aforementioned structures. This configuration was used to measure the capacitance (C) at 1.0 MHz from which the ϵ_r of the ferroelectric layer was thereby calculated using Eq. (1),

$$\epsilon_r = \frac{Cd}{\epsilon_o A} \qquad (1)$$

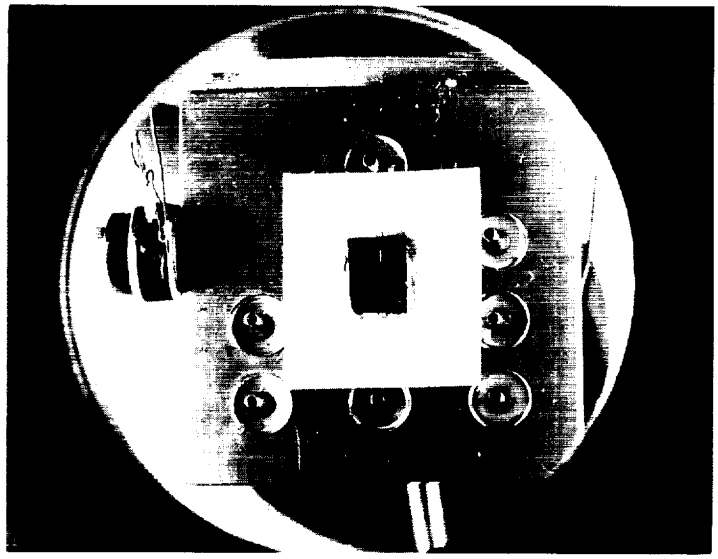

Figure 3. Sample mounted inside vacuum chamber showing electrical feedthroughs.

where A represents the area of the gold contact, d represents the thickness of the ferroelectric layer, and $\epsilon_0=8.854\times10^{-12}$ F/m represents the permitivity of free space.

Values of ϵ_r for the ferroelectric layers were obtained as a function of temperature and dc bias. An HP-4192A LF impedance analyzer, a CTI-Cryogenics closed-cycle, helium gas refrigerator, and a Lake Shore Cryotronics 805 temperature controller all linked through an IEEE-488 data bus to an HP 9000-300 computer served as the main components of the experimental configuration, shown in Figure 2, which performed these measurements. As seen in Figure 3, the sample, known as the device-under-test (DUT), was mounted on a sample holder having electrical feedthroughs for dc bias. The temperature sensor, a silicon diode, was bolted directly to the sample holder. The sample holder was bolted to the cold head of the refrigerator to allow for measurements at cryogenic temperatures. An HP-Basic computer program was written to automate the measurement system allowing the user to take data as a function of temperature at a constant dc voltage and as a function of dc voltage at a constant temperature. All measurements were taken at "user-input" pre-selected conditions. Pre-selected dc voltage conditions were directly outputted to the impedance analyzer and

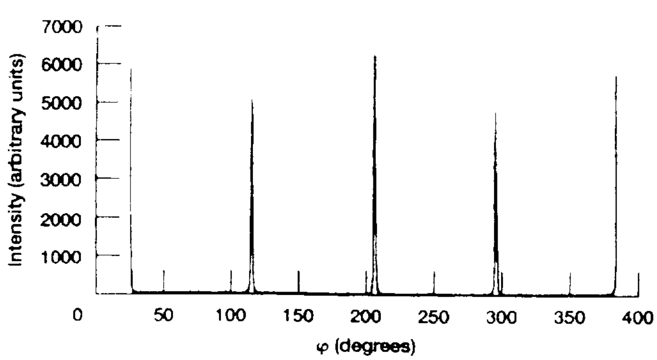

Figure 4. Phi scan about the BST (420) peak. Four-fold symmetry shows good in-plane alignment of the BST film on the YBCO film.

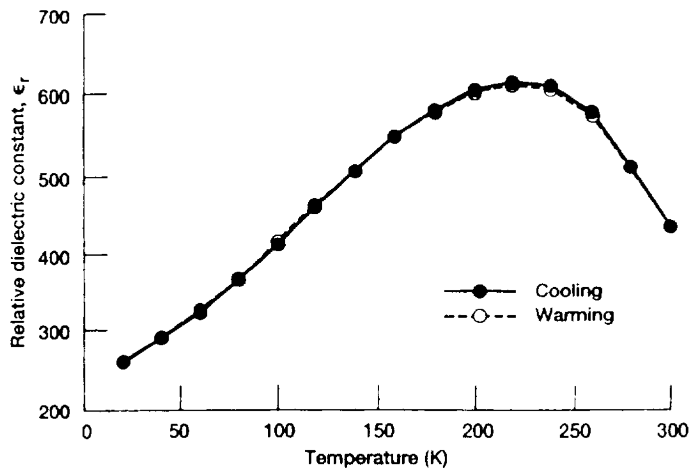

Figure 5. Dielectric constant versus temperature for the BST (Ba:Sr, 0.50:0.50) layer in the BST/YBCO/$LaAlO_3$ structure at 1.0 MHz and zero **E**.

temperatures conditions were outputted as "set-points" to the temperature controller which controlled and monitored the temperature of the DUT. When specified conditions were met, data on the DUT's capacitance and loss tangent ($\tan\delta$) were measured by the impedance analyzer and stored along with the DUT's ϵ_r, calculated by the computer program using Eq. 1, to a 3.5 inch disk for further analysis.

RESULTS

The ferroelectric layers were analyzed using x-ray diffraction (XRD). As seen in Figure 4, Phi scans about the (420) peak of the BST film show in-plane epitaxy with the underlying YBCO film. However, diffraction peaks for the MOD BST film were very weak at high angles and there was no evidence of in-plane epitaxy.

For the electrical characterization of the samples, the first test undertaken focused on measuring ϵ_r as a function of temperature at a frequency of 1.0 MHz and at zero E. Measurements were taken at intervals of 20 K during cooling from 300 to 20 K and during

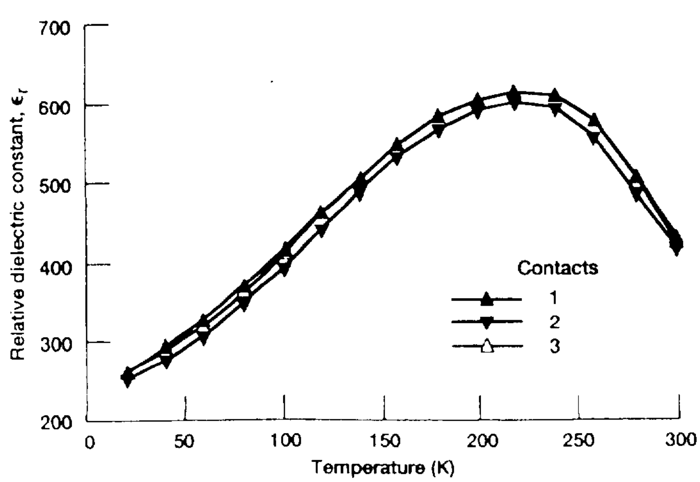

Figure 6. Dielectric constant values of different contacts versus temperature for the BST (Ba:Sr, 0.50:0.50) layer in the BST/YBCO/$LaAlO_3$ structure at 1.0 MHz and zero **E**.

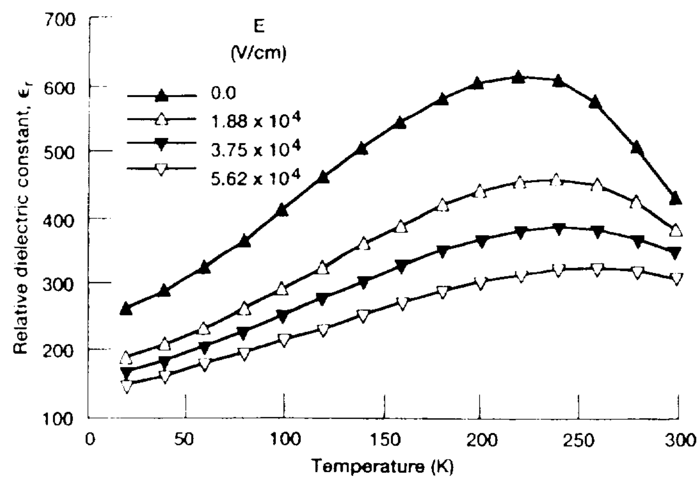

Figure 7. Dielectric constant versus temperature for the BST (Ba:Sr, 0.50:0.50) layer in the BST/YBCO/LaAlO$_3$ structure at 1.0 MHz and several values of **E**.

warming from 20 to 300 K to determine if the samples were sensitive to the temperature cycling. At room temperature, values of ϵ_r and tanδ for the BST sample of 425 and 0.040, respectively, were obtained. Neither the ϵ_r data, seen in Figure 5, nor the tanδ data showed any signs of temperature hysteresis as a result of the temperature cycling. Figure 6 shows ϵ_r data from different contacts across the sample's surface taken under the same temperature and bias conditions. This test was performed to determine the degree of uniformity of the BST film. Note that the obtained results are quantitatively and qualitatively very similar. This suggests excellent composition and structural (i.e., thickness) uniformity throughout the BST layer. The behavior of ϵ_r and tanδ as a function of **E** was also investigated. The results are shown in Figure 7 and Figure 8. In Figure 7, each curve represents the ϵ_r of the BST layer as a function of temperature at a particular **E** value. Note that there is a decrease in ϵ_r as the magnitude of the applied field is increased. Maximum variation in ϵ_r, from ϵ_r=610 to ϵ_r=300, occurred at a temperature near 220 K. For practical microwave components, such as tunable

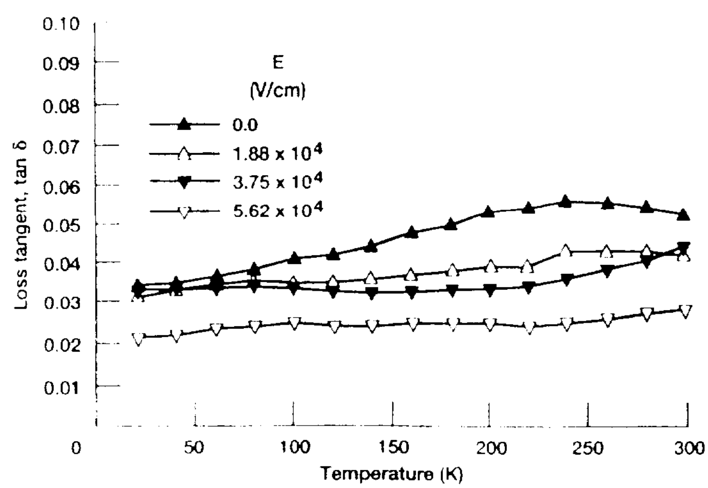

Figure 8. Loss tangent versus temperature for the BST (Ba:Sr, 0.50:0.50) layer in the BST/YBCO/LaAlO$_3$ structure at 1.0 MHz and several values of **E**.

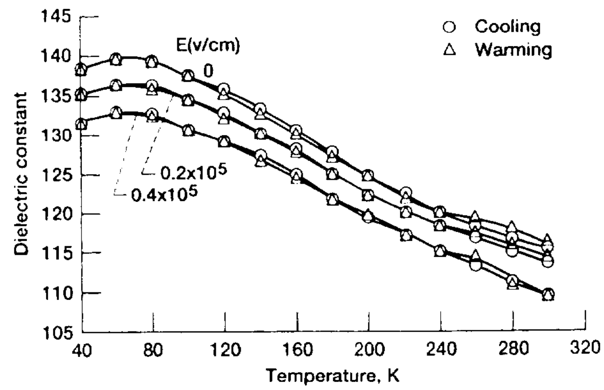

Figure 9. Dielectric constant versus temperature for a polycrystalline, 500 nm thick, metalorganic deposited MOD BST (Ba:Sr, 0.08:0.92) layer in the BST/YBCO/$LaAlO_3$ structure at 1.0 MHz and several values of **E**.

capacitors, filters, and phase shifters, a change in ϵ_r from 300 to 610 will create a frequency range within which the component can be tuned[5-7]. At 77 K, a temperature at which YBCO is in the superconducting state, values of ϵ_r changed from 180 to 360 in the range of $0V/cm \leq \mathbf{E} \leq 5.62x10^4V/cm$. At this temperature, both the HTS film's low conductor losses as well as the ferroelectric's tunability could be fully exploited.

Figure 8 shows results of tanδ as a function of temperature and **E**. It can be seen that the values for tanδ vary slightly as a function of **E** in the aforementioned field range. This result is very important for microwave applications since it shows that the ϵ_r can be altered without dramatically enhancing the ferroelectric's microwave losses. The range of tunability for the polycrystalline, 500 nm thick, MOD BST film over $0V/cm \leq \mathbf{E} \leq 4.0x10^4V/cm$ at 60 K was only 3.6 percent, see Figure 9. In addition, tanδ was very sensitive to **E** as shown in Figure 10. We dismiss the possibility that the lower tuning in the MOD BST film is due to the composition differences since measurements on epitaxial STO and $Ba_{0.10}Sr_{0.90}TiO_3$ films deposited on YBCO displayed ϵ_r values that could be decreased by 30 and 10 percent respectively under the same electric field[8]. Therefore, the fact that the tuning was lower for the MOD BST film suggests that the lack of epitaxy decreases tuning and also increases microwave losses.

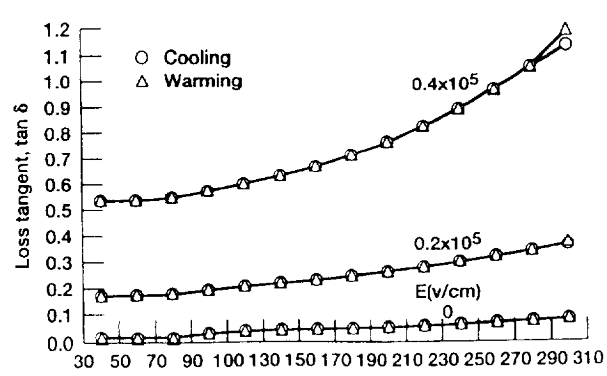

Figure 10. Loss tangent versus temperature for a polycrystalline, 500 nm thick, metalorganic deposited MOD BST (Ba:Sr, 0.08:0.92) layer in the BST/YBCO/$LaAlO_3$ structure at 1.0 MHz and several values of **E**.

CONCLUSION

A ϵ_r of 425 and a tanδ of 0.040 were measured at 298 K, 1.0 MHz, and zero **E** for an epitaxial BST ferroelectric layer. At 77 K, 1.0 MHz, and zero **E**, a ϵ_r of 360 and a tanδ of 0.036 were measured. Maximum change in ϵ_r, from 300 to 610, was observed at 220 K in the **E** range of $0V/cm \leq \mathbf{E} \leq 5.62x10^4 V/cm$ with minimal change in tanδ. The range of tunability for a polycrystalline, 500 nm thick, MOD BST film was very small, 3.6 percent, and tanδ increased markedly with **E** over $0V/cm \leq \mathbf{E} \leq 4.0x10^4 V/cm$. This suggests that the lack of epitaxy could adversely affect the tuning range and the microwave losses of ferroelectric/HTS based microwave components.

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REFERENCES

1. F.A. Miranda, S.S. Toncich, and K.B. Bhasin, Performance of two-pole bandpass filters photodefined on double-sided Y-Ba-Cu-O and Tl-Ba-Ca-Cu-O thin films, *Microwave and Optical Tech. Lett.* 6:752-755 (1993).
2. F.A. Miranda, Microwave properties of Tl-Ba-Ca-Cu-O thin films, *Supercond. Sci. Technol.* 6:605-612 (1993).
3. A.M. Hermann, A. Naziripour, A. Outzourhit, and C.H. Mueller, Tunable microwave resonators based on sputtered Tl-Ba-Ca-Cu-O and Ba-Sr-Ti-O thin films, in: "Low Temperature Electronics and High Temperature Superconductivity," C.L. Claeys, ed., The Electrochemical Society, Inc., Pennington (1995), p. 35.
4. H.D. Wu, Z. Zheng, F. Barnes, C.H. Jackson, A. Kain, and J.D. Cuchiaro, Voltage tunable capacitors using high temperature superconductors and ferroelectrics, *IEEE Trans. Appl. Superconductivity* 4:156-160 (1994).
5. O.G.Vendik, L.T.Ter-Martirosyan, A.I.Dedyk, S.F.Karmanenko, and R.A.Chakalov, High-T_c Superconductivity: New Applications of Ferroelectrics at Microwave Frequencies, *Ferroelectrics* 144:33-43 (1993).
6. S.S.Gevorgian, D.I.Kaparkov, and O.G.Vendik, Electrically Controlled HTSC/Ferroelectric Coplanar Waveguide, *IEE Proc. Microwave Antennas Propagation* 141:501-503 (1994).
7. O.G.Vendik, I.Mironenko, and L.T.Ter-Martirosyan, Superconductors Spur Applications of Ferroelectric Films, *Microwaves and RF*, 67-70 (July, 1994).
8. F.A. Miranda, C.H. Mueller, G.A. Koepf, and R.M. Yandrofski, Electrical response of ferroelectric/superconducting/dielectric $Ba_xSr_{1-x}TiO_3$/$YBa_2Cu_3O_{7-\delta}$/$LaAlO_3$ thin film multilayer structures, *Supercond. Sci. Technol.* 8:755-763 (1995).